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GATEWAY

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Figure 1. Biomechanical testing of load carriage volunteer. Reflective markers (light circles) outline major body segments and force platform. Linked segment model and force coordinate system overlay image.

Using Biomechanics to Improve Warfighter Load-Carrying Capability

Col John P. Obusek

Soldiers and Marines are typically required to carry heavy loads in the field. While most of the load is carried in a backpack, some is carried on a belt, harness, the head (helmet), and in the hands (rifle). U.S. Army Field Manual 21-8, *Foot Marches*, states that a standard fighting load, the load a soldier can expect to carry during combat, will weigh up to 48 lbs. Approach march loads, consisting of the minimal equipment and supplies necessary for prolonged operations and weighing up to 72 lbs., can be expected on missions where enemy contact is likely and loads of up to 150 lbs. may be required during emergency missions. Recent studies at the Marine Corps Infantry Officer Basic Training Course revealed operational loads ranging from 105 to 150 lbs. For many individuals, these loads approach or exceed 100 percent of their body weight and place considerable stress on their musculoskeletal systems. Furthermore, the physiological strain associated with such loads causes both physical and mental fatigue, as well as injuries, leading to a decrease in warfighter performance on the battlefield. Although considerable effort is being made

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toward making carried equipment lighter, the anticipated addition of new digital technology to the warfighter of the future will undoubtedly offset these weight reductions.

Figure 2. Adjustable center of mass pack. Grayed portion depicts alternate vertical locations for the load and dark circles represent alternate horizontal locations for the load. Reflective markers indicate center of mass position in sagittal and frontal planes for selected load placement.

Until recently, load carriage research has focused primarily on quantifying the metabolic energy cost of carrying loads. Metabolic energy cost, measured as the rate of oxygen consumption, represents the net physiological cost to the body of doing work. It is related to an individual's aerobic fitness level, and is an important variable for predicting physical work capacity and fatigue. Although susceptible to variations in terrain type and load distribution, measures of oxygen consumption alone are not sufficiently sensitive to reflect typical biomechanical adaptations to load carriage. Underlying variations in posture, changes in the magnitude and distribution of muscular power generation and shock absorption, and alterations in mechanical stress attenuation can combine to drive changes in physiological cost.

The Center for Military Biomechanics Research (CMBR) is applying the science of biomechanics to improve our understanding of the mechanical aspects of warfighter load carriage and the associated strain on the body. The CMBR uses a three-pronged research approach that integrates biomechanics and physiology, and combines them with measures of warfighter physical performance. The objectives of this research are to improve warfighter load-carrying capability and reduce the likelihood of musculoskeletal injury associated with the carriage of heavy loads.

The CMBR is located at the Soldier System Center, Natick, Massachusetts. It is operated jointly by the U.S. Army Research Institute of Environmental Medicine, a subordinate unit of the U.S. Army Medical Research and Materiel Command, and the Natick Soldier Center, a subordinate unit of the Army Materiel Command. This cooperative arrangement ensures that the medical aspects of load carriage research are appropriately applied to both the doctrinal and the materiel solutions necessary for improving warfighter load-carriage capabilities.

The collection and analysis of kinematic and kinetic data provide the basis for the biomechanics portion of the research program. Soldier volunteers are studied while walking and carrying loads in various experimental and "off-the-shelf" load-carrying configurations. Kinematic data, collected with high-speed infrared cameras, are used to quantify the resulting movement patterns of the body. Small reflective markers are placed on the skin and outline the major body segments. The marker positions in three-dimensional space are recorded up to 240 times per second during the movement. A force platform embedded flush with the floor surface simultaneously records the kinetic data. The kinetic data are used to quantify the net force exerted by the body as the foot strikes the platform and the body (plus load) weight is supported by the leg. A computer integrates the kinematic and kinetic data, and creates a model of the body during walking that displays the recorded movement patterns and calculates the applied forces (see Figure 1 on page 1). Other variables of interest, such as the position, velocity, and acceleration of each body segment, and the resulting joint forces and moments, are also calculated from the model.

Electromyographic (EMG) data may be collected from selected muscle groups of the trunk and legs. These data provide information on the patterns and magnitude of muscle activity during load carriage and may be used to explain the resultant biomechanical work. The relationships between the muscle activity, the biomechanical work performed, and the physiological cost yield a complete description of how a warfighter's body adapts to the stress of carrying heavy loads. This information is used to guide the product developer in the design of efficient individual load-carrying equipment, and to instruct soldiers and Marines in the wear and packing of that equipment. Information on muscular work and power generation is used to guide physical fitness trainers in the development of specific load-carriage-enhancing fitness programs.

A recent study at the CMBR examined the effects of the load center-of-mass (COM) location on the biomechanics and metabolic energy cost of soldiers carrying heavy loads. A custom, external frame backpack (20 lbs.) was fabricated in which the location of a 55 lb.–lead brick load could be moved, resulting in nine different COM positions (see Figure 2). A center of mass location, high and close to the body, resulted in significantly lower joint reaction forces in the joints of the legs. High joint reaction forces have been associated with accelerating the degenerative changes that normally occur on the load-bearing joint surfaces. Thus the consequent reduction in joint reaction force is considered desirable for injury reduction. The high and close-to-the-body center of mass location also resulted in a significant reduction (24%) in metabolic energy cost. These results suggest backpack COM placement is an important factor in the design and loading of backpacks, and affects the ability of warfighters to perform sustained load carriage and execute physically demanding tasks following removal of the load at the objective.

The CMBR also performs evaluations of commercially available products that have potential military applications. A comparison between a commercial off-the-shelf (COTS) internal frame pack and the standard U.S. Army Lightweight Carrying Equipment (ALICE) pack revealed reduced energy cost and lower postural deviations when carrying a 75–lb. load in the COTS pack. The lower energy cost and preferred walking posture associated with the commercial pack were attributed to its volume configuration and related load COM location. The taller, narrower commercial pack afforded a more optimal load center of mass placement on the body compared to the ALICE.

Although the internal frame COTS pack was rejected as a replacement for the ALICE pack due, in part, to its excessive heat retention, a similar volume configuration was incorporated into the design of the Modular Lightweight Load Carrying Equipment (MOLLE) pack (see Figure 3). Other biomechanically advantageous characteristics, such as a load-distributing waist belt, were also used in the MOLLE design. The MOLLE prototype was evaluated by the CMBR, and as a result of its demonstrated superior performance characteristics, the MOLLE pack has been accepted as the replacement for the ALICE pack as the standard individual load-carrying equipment for the Army and Marine Corps.

Numerous other variables that can affect load carrying capacity remain to be studied, yet load carriage research remains essentially a militarily unique endeavor. Determining the effects of inclined and uneven terrain, load distribution between the shoulders and the hips, and differences in the pack mass moment of inertia (the tendency of a mass to rotate) on load- carrying capacity are goals of the ongoing CMBR load-carriage research program. These goals are part of a broader Army Science and Technology objective entitled "Load-Carriage Optimization for Enhanced Warfighter Performance" that is in its first year of execution. This five-year joint effort by the Medical Research and Materiel Command and the Army Materiel Command will significantly further our understanding of human load-carrying capacity and result in greater improvements in load-carriage capability for the warfighter of the future.■

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Figure 3. Soldier wearing the new Modular Lightweight Load Carrying Equipment (MOLLE) adopted by the U.S. Marine Corps and currently being tested by the U.S. Army.

Words from the Chief Scientist

The Case for Human Performance Representation in Computer-Generated Forces

a column by **Michael Fineberg**

In the last two issues of GATEWAY, I have written from the perspective of a scientist engaged in integrating the fidelity and variability of human performance into today's computer-generated forces (CGFs). In this article, I will address you from a different point of view, as an observer of the process and politics of human performance modeling (HPM). If I ruffle some feathers or misspeak with regard to your intimate knowledge of the field, I invite you to respond and set me straight.

I'll begin with a little history. During the Cold War, constructing computer-generated Blue and Red forces would have been much simpler had today's technology been available then. At the time, the United States and its allies were faced with the Union of Soviet Socialist Republics (USSR) and the Warsaw Pact. As a result, we conducted most of our training using Soviet equipment, tactics, and capabilities to prepare groups of real soldiers acting as opposing forces. In the post-Cold War era, several potentially hostile regional powers pose serious threats. They have respectable conventional forces and already possess chemical and biological weapons, and are moving closer to having nuclear weapons. These states, motivated by a desire for regional dominance and less inhibited by the notions of mutual deterrence that conditioned the U.S.-Soviet relationship, may be more likely to use such weapons in major regional conflicts where they feel that their survival as viable states is at risk.

The bottom line is that we will be faced with a whole new group of adversaries and a qualitatively different set of missions than we have experienced in the last 50 years. In the future, we will fight new opponents in novel situations who will be using various types of equipment with a wide variety of tactics. In addition, these opponents will come from several cultures with different value structures and perceptions of why they are fighting. In this new world, one side's victory will not always be perceived as the other side's defeat. This has already been demonstrated in Iraq, Bosnia, and now Kosovo.

Fortunately, during the time that the strategic situation was changing, military modeling and simulation (M&S) underwent a quantum leap in maturation propelled by conceptual and software innovations and a geometric growth in computing power. These advances which resulted in computer-based simulations of warfare (constructive simulations) and networks of manned weapon-system simulators augmented by CGFs, were brought to bear on the analyses, experimentation, and training necessary to prepare U.S. forces to engage unknown multiple threats.

As I see it, there are two problems with using today's CGFs for command group training, tactical analyses, or simulation-based acquisition in the distributed simulation environment. First, CGFs behave as automata on the virtual battlefield. That is, they do the right thing all the time (when they work properly). If they are predictable, a smart student or analyst will quickly see this and take advantage of the inflexibility of CGF behavior to "beat the game." Second, even if CGFs performed as if they were under human command and control, they would today be fighting with U.S.-NATO tactics and equipment. Thus we would be perpetuating our propensity to assume that our enemy is like us. This situation is aggravated further by another factor. While weather, lighting, and other environmental conditions (e.g., propagation of obscurants and chemical and biological weapons) on the virtual battlefield are becoming more and more representative, current CGFs remain "insensitive" to these new simulated battlefield stimuli. Consequently, the results of an exercise will not be valid for real-world application. Therefore, we must conduct our virtual exercises with realistic Blue CGFs and against synthetic opposing forces that represent the tactics and fighting styles of our future adversaries.

While the issues that influence the modeling of individual and group behaviors are different than they were during the Cold War, the actions neces-

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sary to represent critical combatant behaviors are similar. These actions begin with establishing a conceptual framework to describe combat behavior and, from this structure, developing operational definitions and a taxonomy for classifying individual and group behaviors. The Defense Modeling and Simulation Office (DMSO) has already accomplished this. Further actions include (a) developing guidelines for constructing accredited behavioral representations of individuals and friendly, neutral, and hostile forces; (b) establishing requirements and priorities for modeling critical aspects of individual and group behavior in combat and in operations other than war; and (c) developing initial prototypes of selected generic forces specified by behavioral categories and definitions.

Once these developmental steps are accomplished, behavioral representations must be provided to the M&S community, standard interfaces must be developed, assessment criteria and methodologies must be designed, better knowledge engineering techniques must be developed, and overall combatant behavior models must be developed using generic model components.

Since 1995, many research efforts have been started that purport to integrate human performance variables in computer-generated forces. They were undertaken by several organizations including DMSO, the Army Research Institute, the Office of Naval Research, DARPA, the Naval Air Warfare Center Training Systems Division, and the Federal Highway Administration to name a few. To my chagrin, none of the initiators of these research efforts appeared to know of the others' work and all but the Office of Naval Research seemed to be unaware of the seminal work done by DMSO. From my position as technical director and chief scientist of CSERIAC, an organization devoted to the collection, analysis, and dissemination of scientific and technical information in human factors, this is a major problem. There is so much urgently important work to be done in HPM and so little money, that it is painful to witness such duplication of effort. My plea to all of you working in HPM for virtual simulation is to join us in a campaign to pool our efforts. If you are engaged in or planning HPM projects, I urge you to contact me or Dr. Ruth Willis at DMSO and let us know what you are doing. As always, I may be reached via e-mail at fineberg_michael@bah.com or via telephone at (703) 289-5120. And Dr. Willis may be reached via e-mail at rpwillis@msis.dmso.mil or via telephone at (703) 824-3438. Let's build on the results of our colleagues' work and thus enhance our contributions to our warfighters and to the state-of-the-art. ■

calendar

sep

September 15-October 15, 1999
Second International Cyberspace Conference on Ergonomics
This is a virtual conference to be found on your local computer. Details at http://cyberg.curtin.edu.au/

Houston, TX, USA. September 27-October 1, 1999
43rd Annual Meeting of the Human Factors and Ergonomics Society
Contact HFES, PO Box 1369, Santa Monica, CA 90406, USA. Tel: (310) 394-1811, Fax: (310) 394-9793, URL: http://www.hfes.org/Meetings/AM-1999.html

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Yellow Springs, OH, USA. October 19-21, 1999
Essentials of Anthropometry
Contact Anthrotech (formerly Anthropology Research Project, Inc.), 503 Xenia Avenue, Yellow Springs, OH 45387, USA. Tel: (937) 767-7226, Fax: (937) 767-9350, E-mail: belva@anthrotech.net, URL: http://www.arp-online.com

St. Louis, MO, USA. October 24-26, 1999
Workplace Safety & Health Training Conference
Contact SOPHE/NIOSH Conference, 750 First Street, NE, #910, Washington, DC 20002-4242, USA. Fax: (202) 408-9815, URL: http://www.cdc.gov/niosh

nov

Albuquerque, NM, USA. Nov 1-4, 1999
43rd Biennial Meeting of the U.S. Department of Defense Human Factors Engineering Technical Advisory Group
Contact Sheryl Cosing, 10822 Crippen Vale Court, Reston, VA 20194. Tel: (703) 925-9791, Fax: (703) 925-9644, E-mail: sherylynn@aol.com, URL: http://dticam.dtic.mil/hftag/hftag.html. *Meeting is open to all government personnel and others by specific invitation.*

Dear CSERIAC

To show the diversity of support that CSERIAC provides, the column below contains a sampling of some of the more interesting questions asked of CSERIAC. In response to these questions, CSERIAC conducts literature and reference searches, and, in some cases, consults with subject area experts.

These questions were compiled by Debra Urzi, Human Factors Engineer. If you would like to comment on any of these questions or issues related to them, please write to "Dear CSERIAC" at the address found on the back cover of GATEWAY.

- An aerospace engineer from Connecticut contacted CSERIAC to obtain anthropometric dimension data for sitting eye height, acromial height, and thumbtip reach for short personnel (height below 1700 mm).

- A representative for an eastern plastics resource center requested information regarding software or models relevant to load pushing and pulling.

- A college student in England contacted CSERIAC to request information on virtual reality and education.

- A representative from a school supply company requested anthropometric information regarding children and school furniture.

- A representative from a well-known clothing manufacturer asked about military standards for cold-weather boots.

- A U.S. Air Force commander requested information on the development, testing, and justification of the standard "T" aircraft cockpit instrument arrangement.

- A principle engineer for a large corporation in the U.S. Midwest requested information relevant to the modeling of human skin displacement and deformation.

- A researcher from the National Transportation Safety Board sought information on the amount of force a pilot would likely apply to a rudder pedal, with attention to seat design, pilot age, and pilot height. The client was particularly interested in the 737 aircraft.

- An engineer from a heavy-equipment manufacturer asked for information on the correlation and anthropometric prediction of sitting knee height using stature.

Cognitive Cockpit Systems
From Flight/Mission Management Towards Knowledge-based Cockpit Assistant Systems

Dr. Reiner Onken

Editor's note: Following is a synopsis of a presentation by Dr. Reiner Onken, Professor of Flight Mechanics and Flight Guidance for the University of German Armed Forces, Munich, Germany. He was a guest speaker in the Human-Technology Integration Colloquium Series sponsored by the Human Effectiveness Directorate of the Air Force Research Laboratory. This synopsis was prepared by Eric Geiselman, Engineering Research Psychologist, Visual Displays Branch, Human Effectiveness Directorate, Air Force Research Laboratory. JAL

What improves flightdeck situation awareness more than two pilots? According to Dr. Reiner Onken the answer is simple: a third pilot. While enhanced situation awareness is desirable, the addition of a third pilot is incompatible with the ongoing trend to reduce the number of flightdeck personnel. Dr. Onken's solution to this paradox is to design crewmember functional attributes directly into an enhanced version of the flight management system (FMS). This approach promises to go beyond current sequential task allocation automation and toward a more active knowledge-based cognitive cockpit assistant functionality.

The objective of this design methodology and its associated technology is the development of a system that is capable of crewmember-like awareness of the overall situation. The uniqueness of a knowledge-based assistant stems from its ability to cope with human operator error and unusual situations by independently assessing and understanding the current state of the situation relative to the flightcrew's goals and sub-goals. This is made possible primarily by supplying extensive domain knowledge to the system.

Situation awareness functionality is a critical requirement of any system capable of true assistance. In the cockpit, system functionality should be designed to parallel the situation assessment and diagnosis duties which are currently the sole responsibility of the human crew. A cognitive cockpit assistant system includes a central situation analysis component formed of perception and diagnosis sub-components. The perceptual component comprises sensor- and database-supplied information from which the system recognizes relevant events and is able to compare these events to its understanding of the safety and mission goals of the human crew. A diagnosis function acts to continuously monitor the situation and look for conflicts as well as opportunities to exploit events to enhance safety or mission effectiveness. Other

Dr. Reiner Onken, Professor of Flight Mechanics and Flight Guidance for the University of German Armed Forces, Munich, Germany.

modules form appropriate decisions (decision finder) of how to proceed followed by the communication (dialog manager) of recommended actions or reports of an action which has been performed. The dialog manager is also responsible for determining the best communication modality to be used for the given condition. The communication is designed to help equalize the human's and the system's situation awareness, referred to as the system's *situation healing activity*.

The system is made continuously aware of the state of the human user by both active and passive means. Actively, the system employs sensors such as cockpit cameras to derive head and eye movement. Passively, a human factors information database is included in the system's static database repertoire. The assistant system's dynamic knowledge of the present situation and associated goals enables it to anticipate the intent of the human and effectively act as an additional status monitor able to error check those duties conventionally believed to be strictly human.

Dr. Onken and his associates are currently testing the third generation of this technology. A working prototype called CASSY (Cockpit Assistant System) has been flight-tested in a civil transport application. Test pilots' responses were very positive toward the partially capable system. This reinforces the point that an assistant system does not have to include the complete functionality required of pure automation to offer significant operational benefit. Currently, a new system called CAMA (Crew Assistant Military Aircraft) is being readied for test within a military bomber scenario. Dr. Onken points out that the goals and missions among the military and civil transport domains are quickly converging and each will benefit from a knowledge-based assistant system's ability to seamlessly cope with rapidly changing situations. Aviation is not the only place where these methodologies can be beneficially applied. Dr. Onken's human-centered design techniques are being adapted to support such diverse human-machine interfaces as automobile driving, industrial process control, and intelligent training systems. Well beyond the cockpit design examples outlined here, this is a design philosophy. According to Dr. Onken, this paradigm shift will potentially be reflected in future design certification and regulatory language across varied applications. Specifications should require that the machine be designed with assistance to the human operator in mind. To do this, interface design approaches should be developed so that the system more closely parallels human capability. In practice, these systems should not operate by function allocation rules but instead by actively assisting the human to continuously decide who does what, when, and how to most safely and efficiently reach common goals. ■

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Command and Control
Human Performance Modeling

Beth Plott,
Josephine Q. Wojciechowski, &
Patricia W. Kilduff

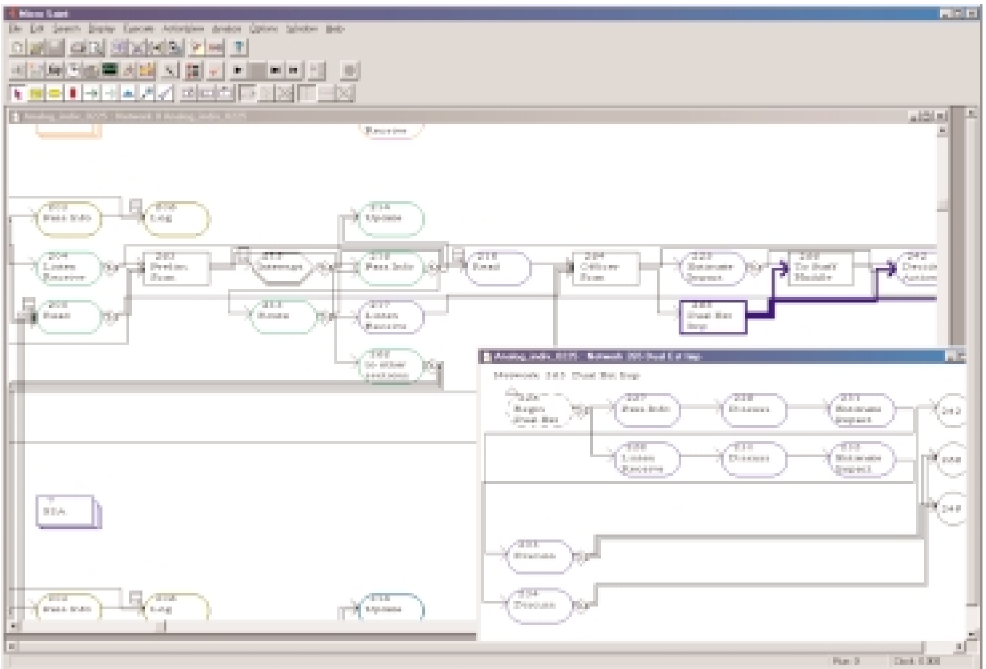

Figure 1. MicroSaint™ model layout.

The future military command and control (C2) process will be altered because of the impact of new information technology and organizational changes. To predict how these changes will impact soldier performance, the Human Research and Engineering Directorate of the U.S. Army Research Laboratory developed models to analyze human performance under current and proposed future operational conditions. C2 soldier task performance and workload were modeled for a "typical" maneuver battalion task force configuration in a future technology-based configuration.

To assess the impact of expected technology and organizational changes on a battalion-level command and control center, the project team developed a human performance model of the C2 tasks performed by soldiers using the baseline and future systems. The model was constructed to quantify task and workload for various configurations and to answer the following questions:

- Can the soldiers complete required tasks in a timely manner?
- Can tasks be reallocated to improve information-processing efficiency?
- Are the soldier workload and utilization at an acceptable level?
- Does working in a moving vehicle significantly impact human performance?

The models were built in three steps:

- Task analysis and workload demand estimation for battalion C2 tasks
- Develop message scenario data
- Develop task network models of task and information flow.

To address the issues discussed above, it was necessary to develop models that are flexible and will allow rapid development. We wanted to be able to evaluate a variety of soldier task allocations, equipment, and scenarios, ranging from worst to best case, without a lengthy development and analysis effort. Discrete-event processing models are suitable for this type of analysis.

The MicroSaint™ discrete-event simulation tool was used to develop these models, allowing tasks, task sequences, flow logic, task timing, and workload data to be built into executable models. The inputs to the models are message events from the scenario input file, which present an information event stream in a time sequence synchronized to mission activity phases. As these information events enter the model, tasks are triggered and performed in a pattern that reflects the *a priori* logic for task branching, interrupt priorities, time outs, and collaborative (interactive) tasks.

To provide an analytical tool that would be useful to the customer, we implemented unique capabilities. These large models contain approximately 575 tasks and networks. An example of the intelligence staff section network is shown in Figure 1.

The most challenging user requirement was the capability to add new scenario events and change the way in which the human operator responded, without having to alter the developed task network. The size of these models made the task difficult. Creating parameters for the task and scenario data with variable values provided the ability to rapidly perform "what if" analysis. We accomplished this by creating a spreadsheet containing the parameters requiring manipulation. The user can enter the required information directly into a spreadsheet, outside the task network. Replacing values in the spreadsheet, the user changes the logic and flow of the model without reprogramming. The task data include parameters to determine which operator would complete the task, the workload associated with the task, the time required for the task, how the task time is degraded by environmental conditions, and how this task relates to the other tasks being performed. For the scenario, users can alter parameters such as the time the message arrives, where the message enters the model, the radio or digital net it is on, the number of words included, as well as indicators of how the message should move through the system. As the model runs, it reads the branching directions from variables set by the user. This parameterization resulted in a flexible platform through which a user, untrained in modeling and tool syntax, can study a variety of scenarios and configurations.

A six-person-month effort was required to build two models that represent a baseline configuration and a future equipment configuration. Changes in task assignment, scenario events, and workload requirements can be made in less than an hour. Model runs for a 24-hour-long movement scenario take about 15 minutes. Current models are being assessed to determine differences in performance when C2 tasks are completed in a stationary versus moving vehicle.

Analysis

The results from the models were analyzed to assess the differences in the C2 operations on information flow and workload and to identify information-processing bottlenecks and overloads. The outcomes from each model run are analyzed independently and then in comparison. The overall goal of comparative analysis was to discern the impacts of the varying combinations of equipment, functional groupings, and environmental conditions on the C2 information flow and workload. Some of the analytical techniques are listed in Figure 2. Preliminary analysis shows that the impact of future equipment is greater than the impact of environmental conditions such as working in a moving vehicle.

Conclusions

Information flow and task workload models were developed and exercised to provide an analysis and decision-making tool for comparing different personnel and equipment design trade-offs for operating in a C2 environment. The current design of these models allows for ease in "what if" analysis of a complicated system. The model gives quick answers to C2 human performance questions that would be difficult and expensive to answer in field trials.■

Parametric statistical comparisons:

- *Information flow measures*
  - messages dropped, queued, & interrupted
- *Soldier workload measures*
  - cumulative & average utilization
  - workload at specified intervals
  - percent workload
  - task processing times
- *Degradation profiles*
  - stressors (fatigue, noise, vibration, motion sickness)

Trend analysis of frequency tables

- *Information flow measures*
  - reasons for task drops, interruptions, & queues
- *Soldier workload measure*
  - workload profiles for each soldier

Multivariate cluster analysis

- *Workload & utilization measures*

Figure 2. Analysis approach

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